

Tracking U.S. Emissions of Sulfur Hexafluoride

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Acknowledgements

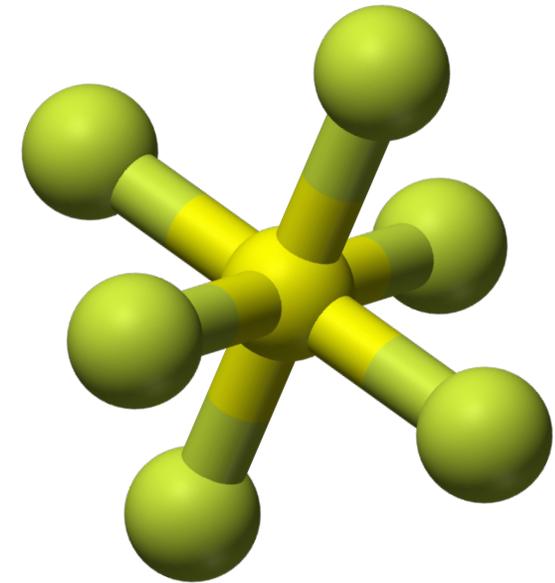
- Stephanie Bogle and Lauren Aepli, U.S. EPA
- Lei Hu and Steve Montzka, U.S. NOAA
- Phil DeCola, University of Maryland and GIST.Earth LLC
- Mollie Averyt, Deborah Harris, Johanna Garfinkle, Shubh Jain, Bikash Acharya, Zeyu Hu, ICF Inc.

Overview

- Atmospheric impacts, sources, and emissions of sulfur hexafluoride (SF_6)
- Estimating U.S. SF_6 emissions
 - Past and current reporting of SF_6 emissions to EPA
 - Voluntary Partnerships
 - Greenhouse Gas Reporting Program
 - Estimating emissions of facilities that don't report
- Verifying U.S. SF_6 emissions using independent datasets
- Potential improvements to estimates

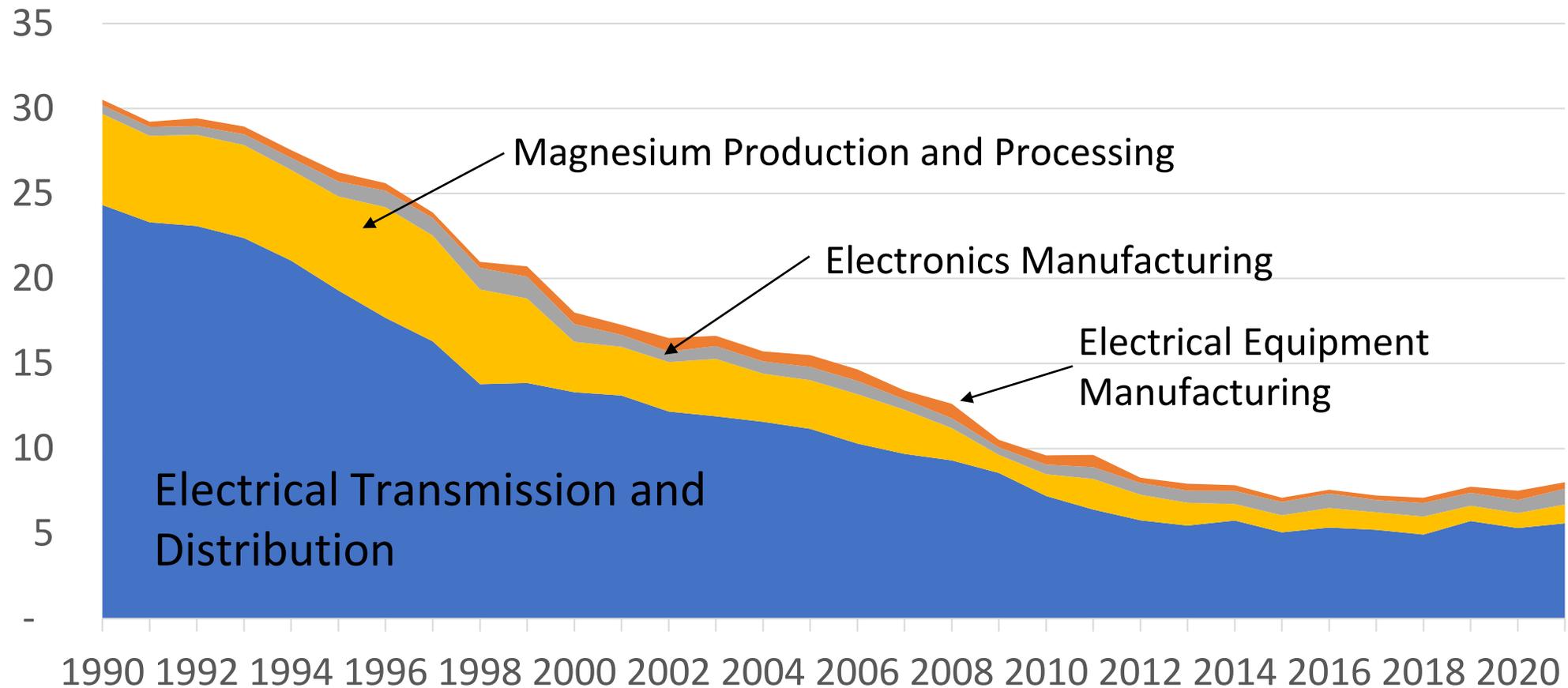
Sulfur Hexafluoride (SF₆)

- Human-made gas mainly emitted from
 - Electrical transmission and distribution equipment
 - Semiconductor manufacturing
 - Magnesium production and processing
- SF₆ is the most powerful GHG known. Kilogram for kilogram, it traps 23,500 times as much heat as carbon dioxide.*
- Because SF₆ has an atmospheric lifetime of 3,200 years, SF₆ emissions are essentially permanent additions to the atmosphere.



*100-year global warming potential from the IPCC Fifth Assessment Report.

2023 US GHG Inventory: Emissions of SF₆ by Industry 1990-2021 (million metric tons CO₂e)



Estimating U.S. SF₆ Emissions

SF₆ Emissions and Supplies: Reporting to EPA

- Late 1990s through 2010: Voluntary partnerships between U.S. EPA and three primary emitting industries provided emissions and related data for varying shares of these industries.
 - Electric power systems provided facility-specific data under SF₆ Emission Reduction Partnership
- 2011-present: Greenhouse Gas Reporting Program (GHGRP) requires reporting of emissions and related data for facilities that exceed applicable thresholds.
 - Electric power systems: Total nameplate capacity > 17,820 pounds (8,082 kg)
 - Electronics and magnesium producers: Emissions > 25,000 metric tons CO₂e
- 2010-present: GHGRP requires reporting of supplies by facilities that produce, import, export, or destroy SF₆ and that exceed applicable thresholds.
 - Producers: No threshold
 - Importers, exporters, and destroyers: Supply streams >25,000 metric tons CO₂e

Key Elements of the GHG Reporting Program

- Annual reporting of GHGs by 41 source categories, accounting for about 85-90% of U.S. GHG emissions
 - 33 types of direct emitters
 - 6 types of suppliers of fuel and industrial GHGs
 - Facilities that inject CO₂ underground for geologic sequestration, enhanced oil recovery, or any other purpose
- Prescribed methods for calculating emissions
- 25,000 metric tons CO₂ equivalent (CO₂e) or more per year reporting threshold for most sources
- All affected entities report all highest-level US parent companies & percentage ownership for each parent company
- Direct reporting to EPA electronically
- EPA verification of GHG data

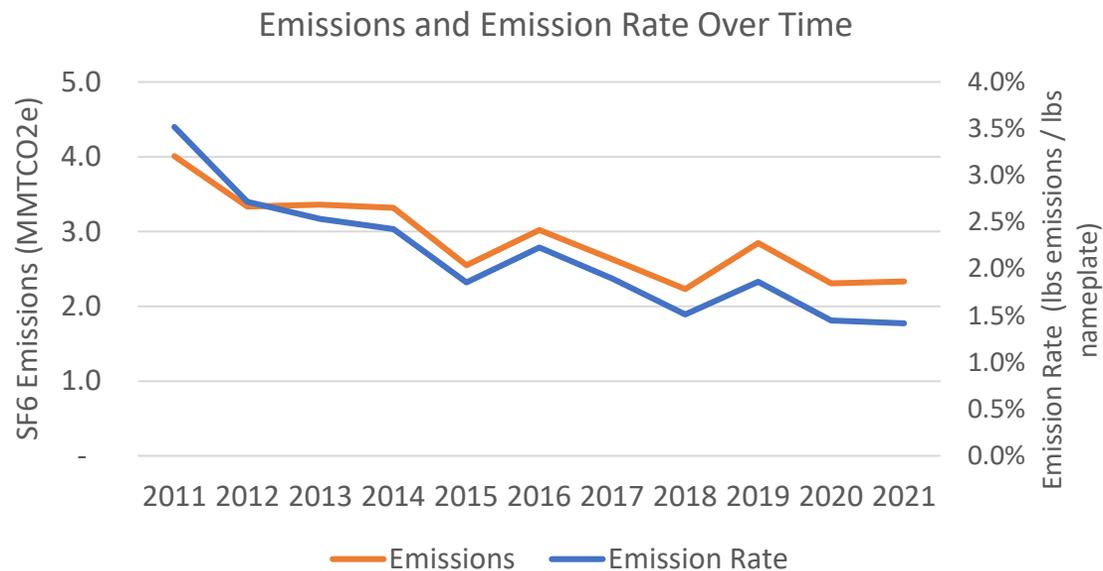
Estimation Methods Used by Reporting Facilities

Source Category	Emissions Calculation Method for Reporting Facilities
Electrical Equipment	Emissions = Consumption SF ₆ – Net Increase in Nameplate Capacity of Equipment (Mass-balance)
Semiconductor Manufacturing	Emissions = Consumption of F-GHGs by Process Type and Wafer Size x Default Emission Factors
Magnesium Production	Emissions = Consumption SF ₆

Emissions from Use of Electrical Equipment Reported under GHGRP (Subpart DD)

	2011		2017	2018	2019	2020	2021
Number of Reporters	117		77	85	86	89	90
Emissions (MMTCO ₂ e)	4.0		2.6	2.2	2.8	2.3	2.3
Beginning Nameplate Capacity (lbs)	10,687,279		13,001,785	13,831,537	14,339,634	14,920,282	15,427,009
Avg. Emission Rate*	3.5%		1.90%	1.51%	1.86%	1.45%	1.42%

*Weighted average



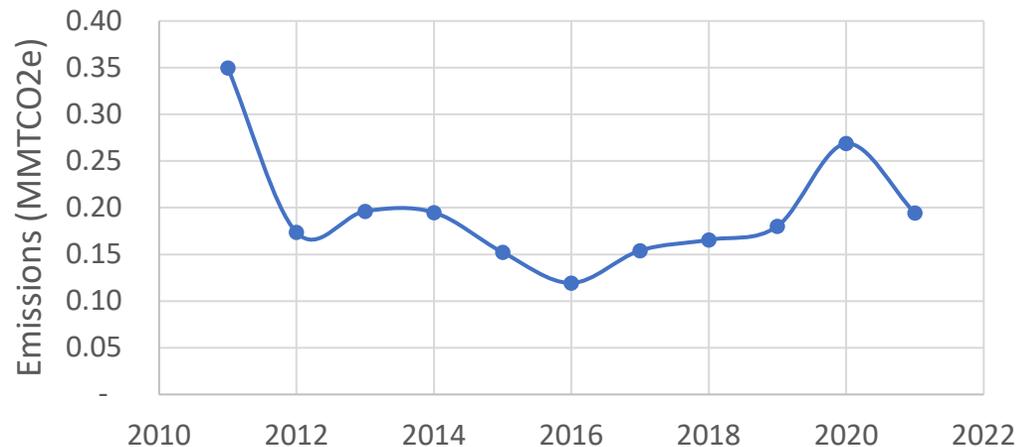
- Over the eleven years of reporting, there has been a **42%** percent reduction in reported emissions
- The emissions reduction is due to both a drop in the emissions rate and a decrease in the number of facilities over time as facilities with low emissions exit the GHGRP. Reduction has occurred despite ~4% AGR in nameplate capacity.

Emissions from the Manufacture of Electrical Equipment Reported under GHGRP (Subpart SS)

	2011	2017	2018	2019	2020	2021
Number of Reporters	6	6	5	5	5	5
Emissions (MMTCO ₂ e)*	0.35	0.15	0.17	0.18	0.27	0.19
% CF ₄ (% MMTCO ₂ e)	0.1%	0.1%	0%	0.2%	0%	0.5%
Annual Emission Changes		+29%	+7.5%	+8.8%	+49%	-27.6%
Total Emission Changes		-56%	-53%	-49%	-23%	-44%

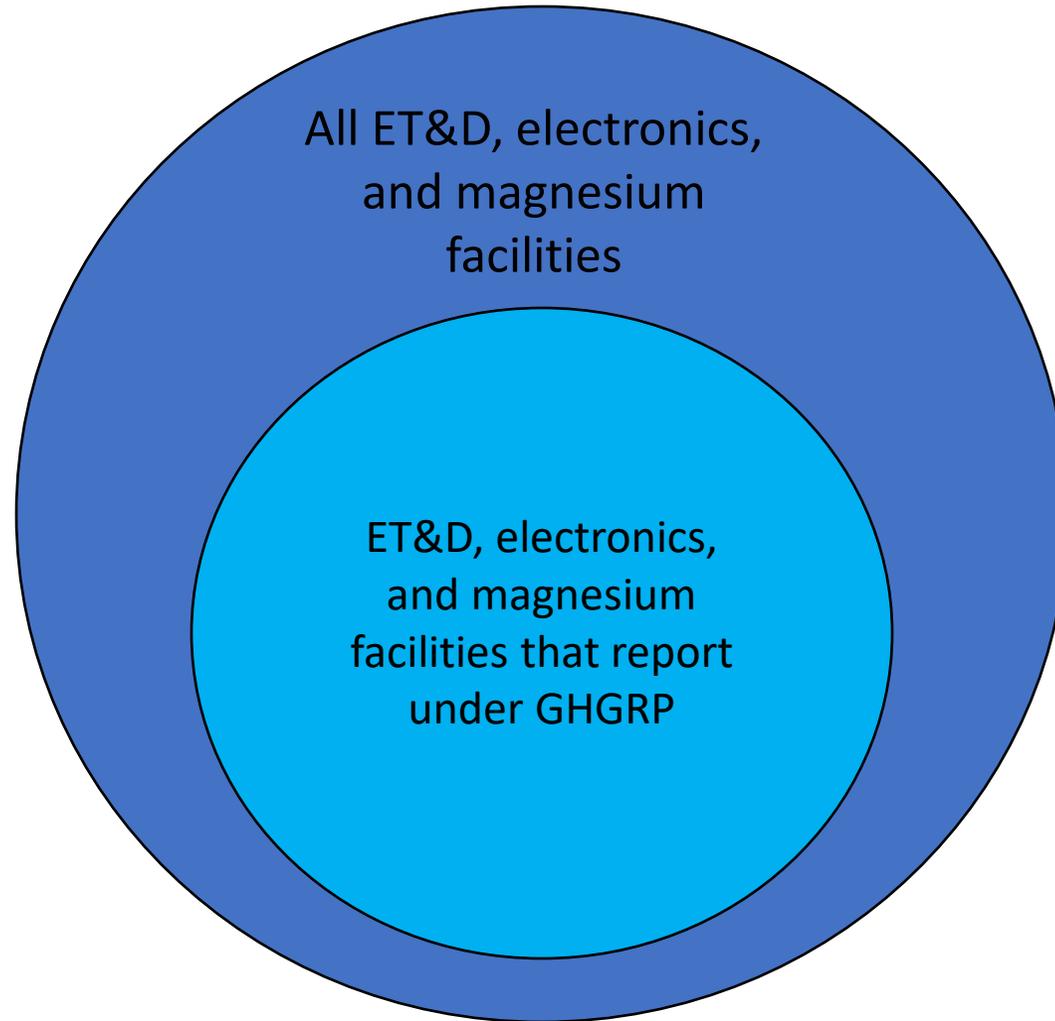
*Does not include combustion emissions reported under subpart C

GHGRP Reported Emissions of SF₆ and CF₄ under Subpart SS



- Emissions from the manufacture and refurbishment of equipment include emissions of both SF₆ and CF₄.
- CF₄ is mixed with SF₆ to avoid liquefaction at low temperatures. Mixed gas circuit breakers are more common in extremely cold climates outside of the United States. No U.S. users of electrical equipment report CF₄ use or emissions.
- Emissions from electrical equipment manufacture reached a low of 0.12 MMTCO₂e in 2016 (a reduction of 66%)
- However, emissions have **increased** since 2016, from 0.12 to 0.19 MMTCO₂e in 2020

Reporters Represent Subsets of their Industries



Scope of GHGRP and Partnership SF₆ Data

Percentage of SF6 Emissions Accounted for by Facilities Reporting to EPA By Source Category

Source	Estimated Percentage of Partnership Emissions Coverage (1999-2009/2010)	Estimated Percentage of GHGRP GHG Emissions Coverage ^a (2010/2011+)
SF6 Users / Emitters		
Electronics Manufacturing	~69-81%	96-97%
Magnesium Production and Processing	88-95%	67-92%
Use of Electric Transmission and Distribution (ET&D) Equipment	60-65%	66-78%
Manufacture of Electric Transmission and Distribution (ET&D) Equipment	N/A	~50%
SF6 Suppliers		
Importers / Exporters	N/A	>95%
Production of Fluorinated Gases	N/A	100%

^a Coverage estimates include both F-GHGs and other GHGs emitted from these sources and show the range in coverage from 2011-2019.

Estimating Emissions by Non-Reporting Facilities

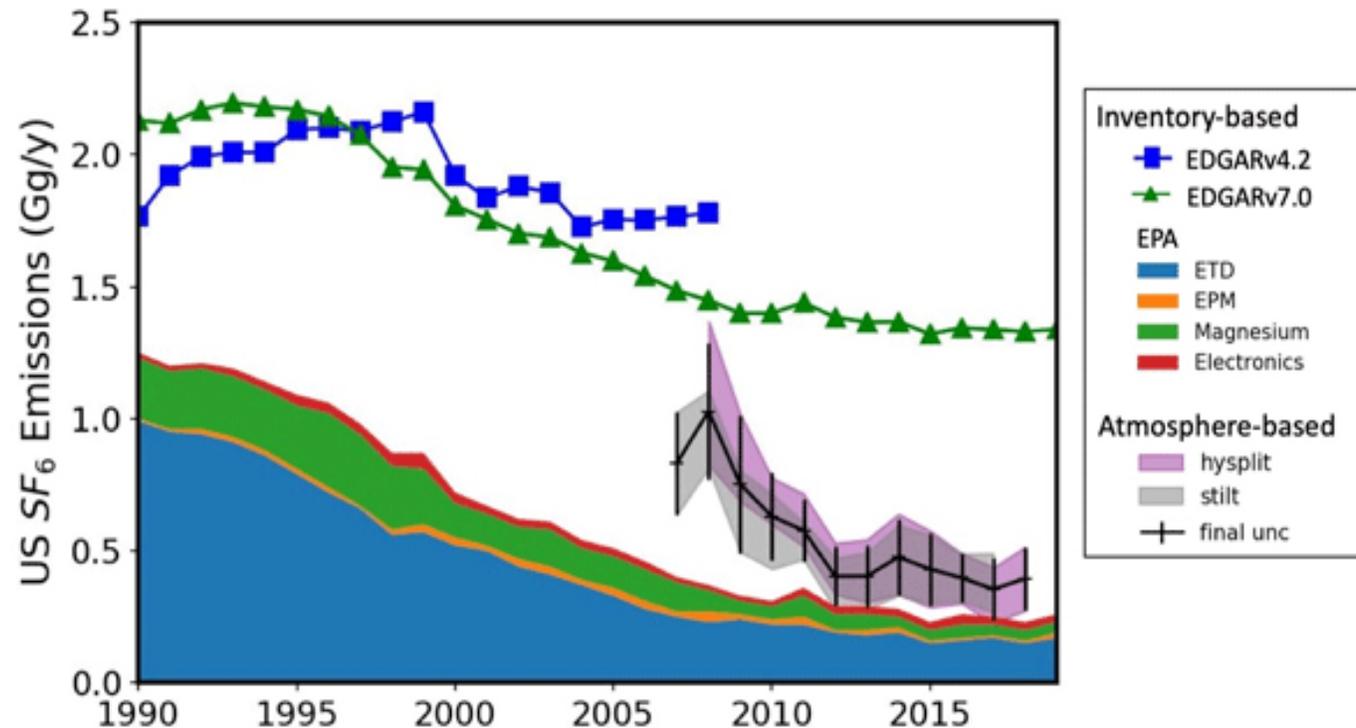
- **ET&D:** Estimate emissions of non-reporting facilities based on length of their transmission lines (miles >35 kV) and historical emission rates (kg SF₆/mile) of reporting facilities.
- **Semiconductors:** Estimate emissions of non-reporting facilities based on index of electronics production (substrate area x number of layers) and emission rates of reporting facilities that don't abate emissions.
- **Magnesium:** Estimate emissions of non-reporting facilities based on USGS estimates of production and emission rates calculated from GHGRP and USGS data.
- **Elec. Equip. manufacturing:** Assume GHGRP accounts for 50% of production capacity and emissions.

Verifying U.S. SF₆ Emissions Using Independent Datasets

Recently Performed Two Comparisons

- SF₆ emissions based on reports from SF₆ users and national statistics (U.S. GHG Inventory estimates) vs. emissions inferred from atmospheric measurements
- SF₆ consumption based on reports from SF₆ users and national statistics vs. supplies based on reports from facilities producing, importing, exporting, and destroying SF₆

Comparison Between U.S. GHGI and Atmosphere-Based Estimates of U.S. Emissions of SF₆



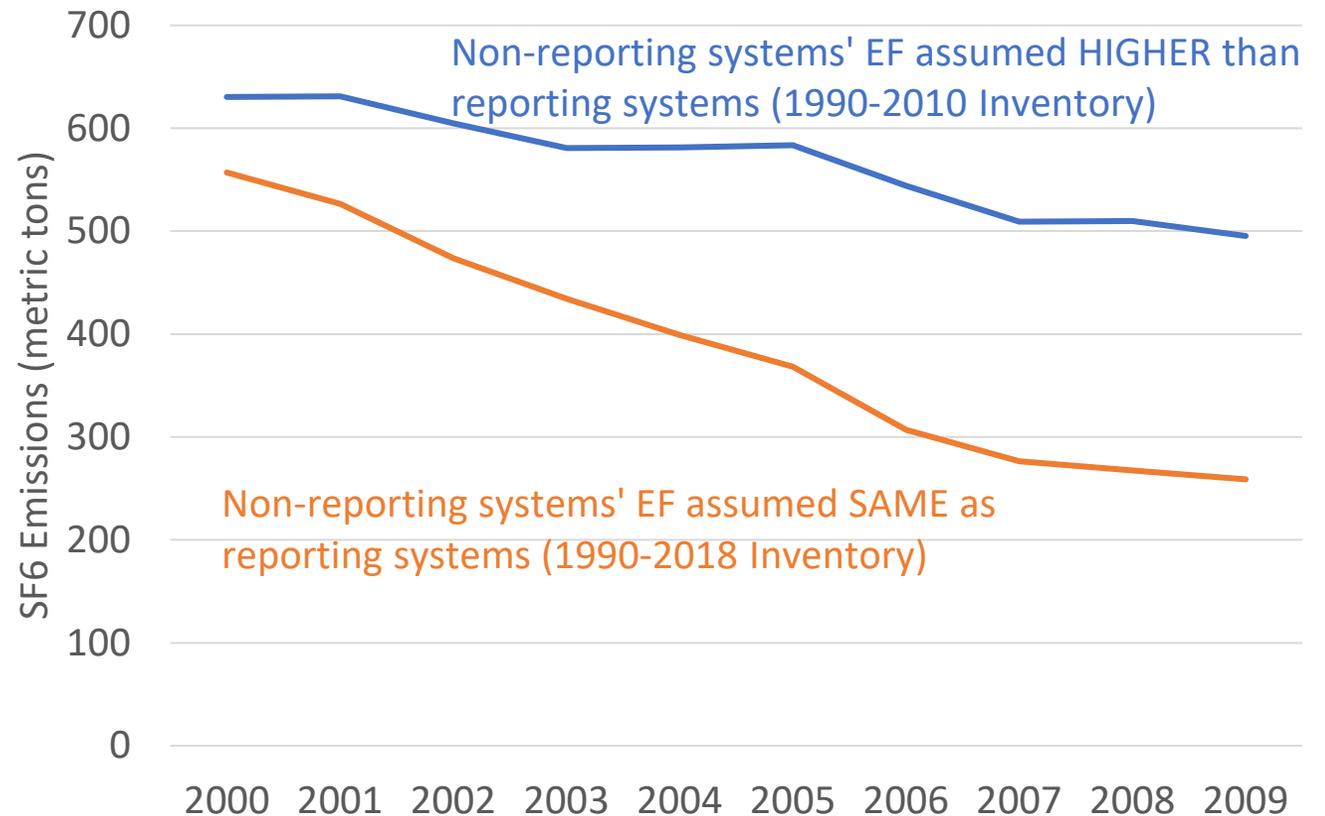
- Activity-based estimates drawn from US GHG Inventory submitted in April 2022 (1990-2020).
- Both US EPA GHG Inventory and atmospheric measurements show a declining trend in US SF₆ emissions.
- US EPA GHGI emissions lower than emissions inferred from atmospheric measurements
 - Gap especially large before 2011.
 - Gap smaller in 2011 and later years, after the GHGRP began.

Source: Hu, L., Ottinger, D., Bogle, S., Montzka, S. A., DeCola, P. L., Dlugokencky, E., Andrews, A., Thoning, K., Sweeney, C., Dutton, G., Aepli, L., and Crowell, A.: Declining, seasonal-varying emissions of sulfur hexafluoride from the United States, *Atmos. Chem. Phys.*, 23, 1437–1448, <https://doi.org/10.5194/acp-23-1437-2023>, 2023.

Activity-Based Estimates Sensitive to Assumed Emission Rate of Non-Reporting ET&D Facilities

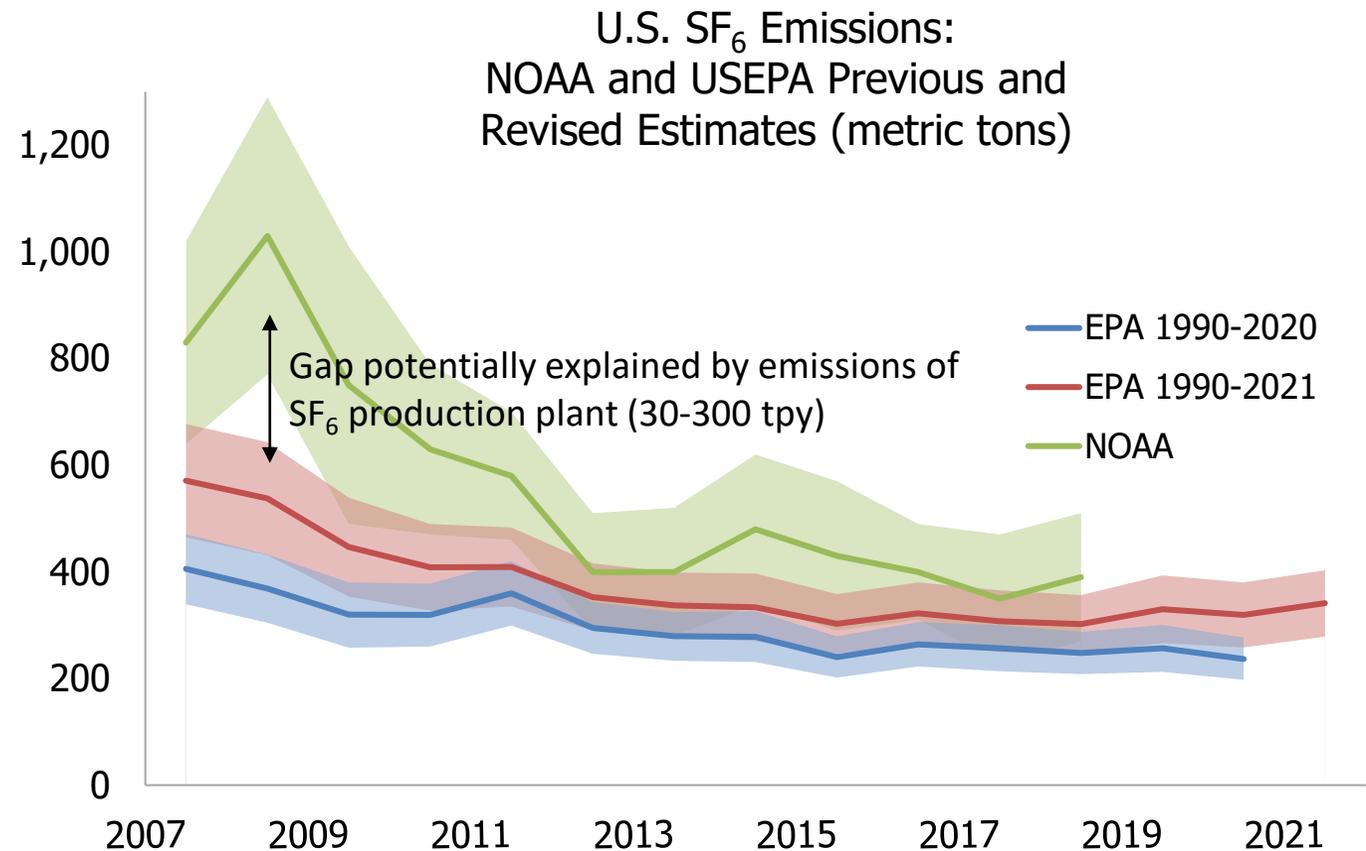
- Facilities reporting under both Partnership and GHGRP reduced emissions significantly, especially in first few years of reporting.
- In US GHG Inventories published *before 2013*, non-reporting facilities were assumed NOT to have reduced their emissions from the 1999 emission rate of Partners.
- In US GHG Inventories published in *2013 and later*, non-reporting facilities were assumed to have reduced their emissions at the SAME rate as reporting facilities throughout the time series.
- In fact, new GHGRP reporters may have acted to reduce emission rate only after draft GHGRP published in 2009.

Estimated Emissions from Electric Power Systems Based on Different Assumptions Re: Emission Rates of Non-Reporting Systems

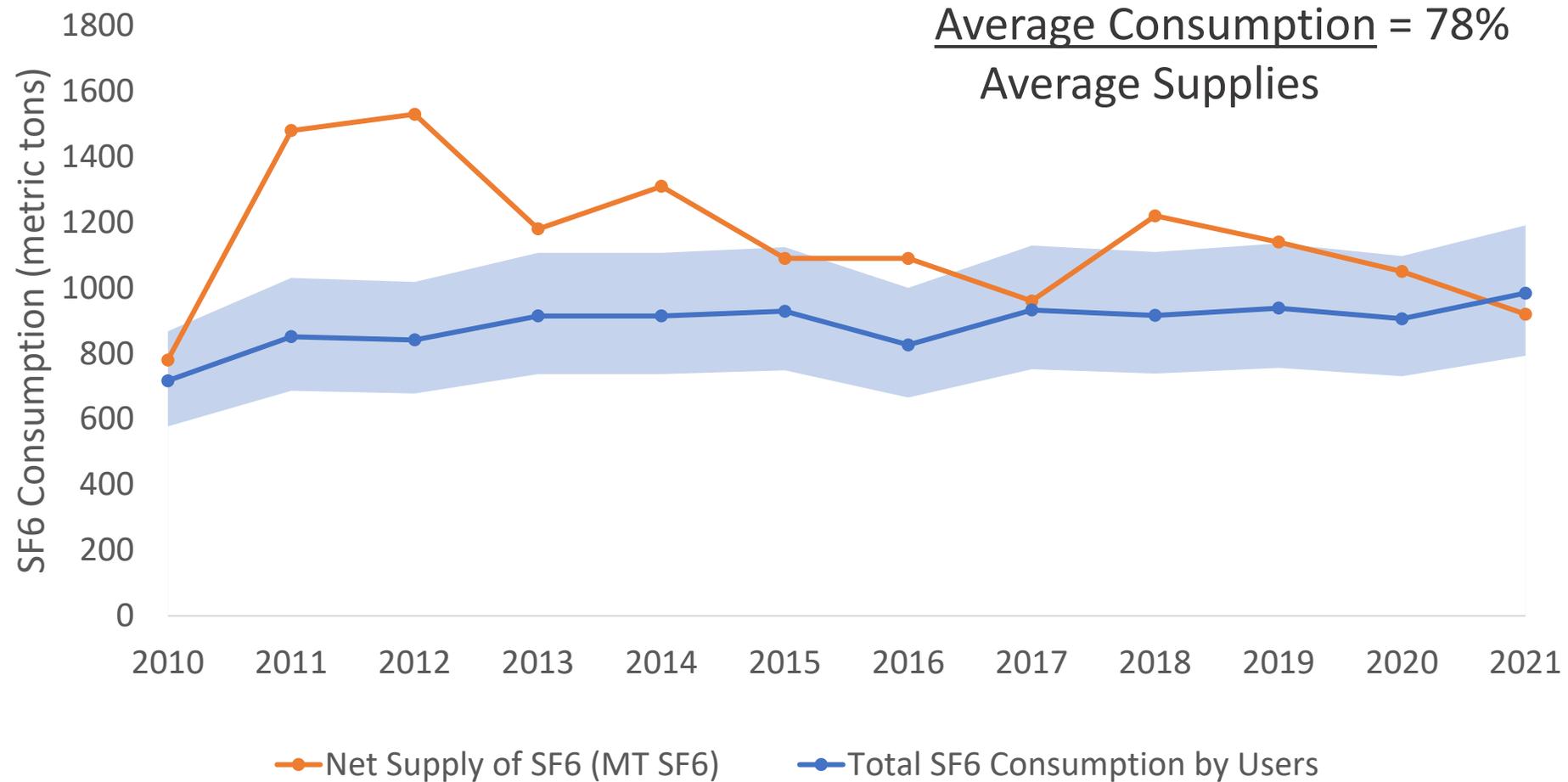


Impact of Revised Assumptions Regarding non-Reporting ET&D Facilities

- From 1999 to 2008, non-reporting facilities now assumed to emit at relatively high rate reported by Partners in 1999.
- From 2009 to 2010, non-reporting facilities assumed to decrease emission rate in anticipation of possible reporting under GHGRP.
- From 2011 to 2021, facilities that began reporting to GHGRP for first time are assigned their reported emissions. For facilities that still did not report, held emission rate at 2010 value.
- Remaining gap from 2007-2010 may be explained by emissions of SF₆ production plant that ceased SF₆ production in 2010. These emissions are not currently captured by US GHG Inventory.



SF₆ Net Supplies vs SF₆ Consumption



Potential Improvements to Estimates

Emissions

- Include emissions from SF₆ production plant, additional uses of SF₆.

Supplies

- Outreach to destruction facilities to improve reporting of destroyed quantities.

Consumption

- Proposed GHGRP requirement for suppliers to report uses of SF₆ and quantities supplied to each, if known.
- Continuing review and refinement of consumption estimates.

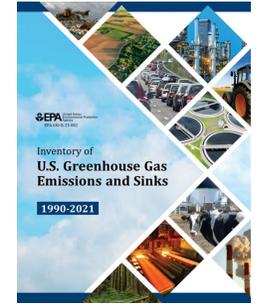
For more information

- For information on the GHGRP: <https://www.epa.gov/ghgreporting>
- For Information on the 1990-2021 Inventory of US Greenhouse Gas Emissions and Sinks: <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>
- SF6 Emission Reduction Partnership: <https://www.epa.gov/eps-partnership>
- Contact: Deborah Ottinger (Ottinger.Deborah@epa.gov)

Thank you for your attention!

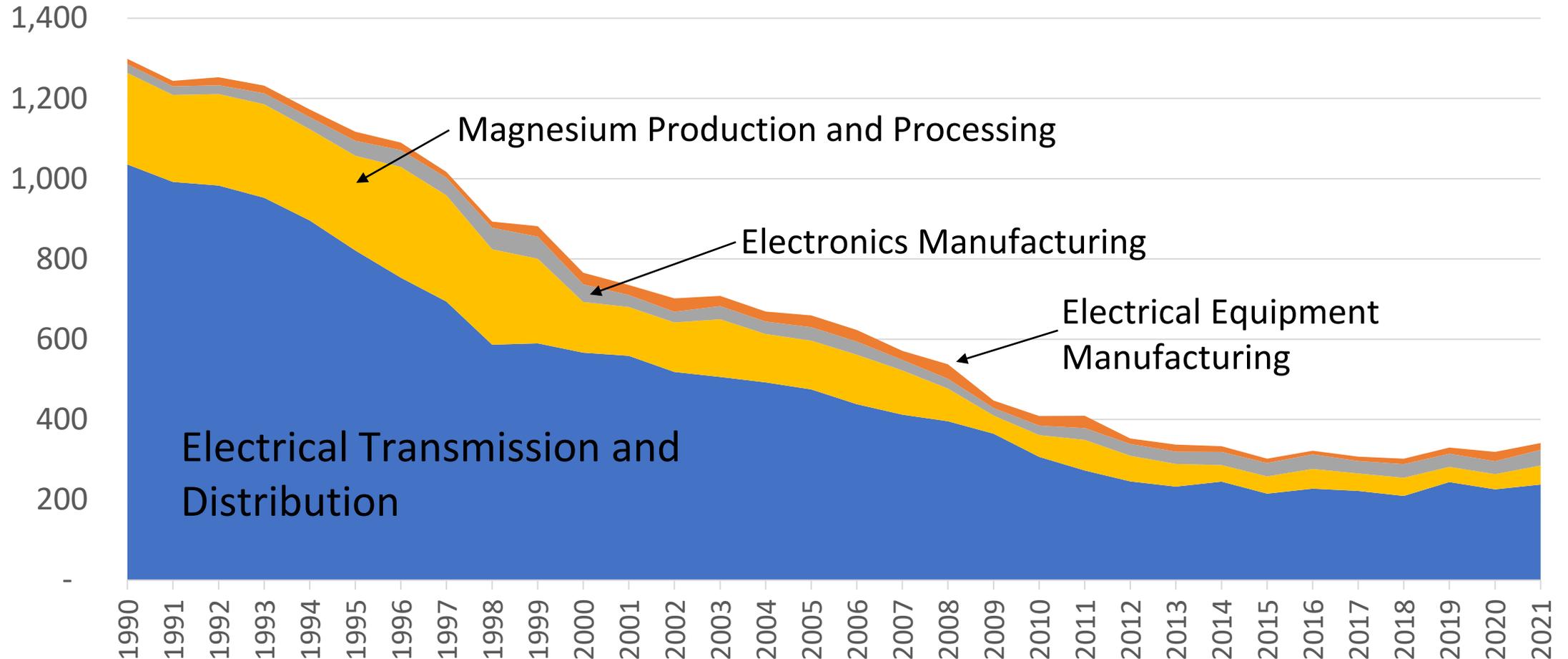
Additional Background

Inventory of U.S. GHG Emissions and Sinks



- EPA annually publishes the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (national Inventory or US GHGI) with help of numerous other U.S. agencies (e.g., EIA, USGS).
 - Includes CO₂, CH₄, N₂O, HFCs, PFCs, SF₆, NF₃
 - Five sectoral chapters compiled using 2006 IPCC Guidelines and its supplements/refinements (Energy, **Industrial Processes and Product Use**, Agriculture, Land Use, Land Use Change and Forestry, and Waste)
 - Time series covered: 1990-2021
 - Uses 100-year global warming potentials (GWPs) from IPCC Fifth Assessment Report (AR5), consistent with UN reporting guidelines
- Represents **official U.S. Government data** on national GHG emissions and sinks over time by gas, source/sink, and economic sector and fulfills annual existing commitments under the UNFCCC
- Produced annually and submitted under UNFCCC **by April 15**
- Policy-neutral but policy-relevant -- input to Nationally Determined Contribution (NDC), legislation, projections, economic analyses, mitigation assessment, regulations, etc.
- Undergoes annual review, including 30-day expert review, 30-day public review, and international peer review (i.e., UNFCCC review)

2023 US GHGI: Emissions of SF₆ by Industry 1990-2021 (metric tons)



Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021. U.S. Environmental Protection Agency. April 2023.

Calculating Emissions under GHGRP: Electrical Transmission & Distribution Equipment Use (Subpart DD)

Subpart DD – Eq. DD-1

User Emissions = (Decrease in Storage Inventory) + (Acquisitions) – (Disbursements) – (Net increase in Total Nameplate Capacity of Equipment Operated)

- Inventory refers to gas inside containers or non-energized equipment. Under the annual mass-balance approach, the beginning of year inventory for a given year must equal the end of year inventory from the prior year in order for emissions to be estimated properly.
- Gas or nameplate associated with hermetically sealed-pressure equipment *must be included* in all of the inputs of the mass-balance formula.

Calculating Emissions under GHGRP: Electrical Transmission & Distribution Equipment Manufacturers (Subpart SS)

- **Subpart SS – Eq. SS-1**

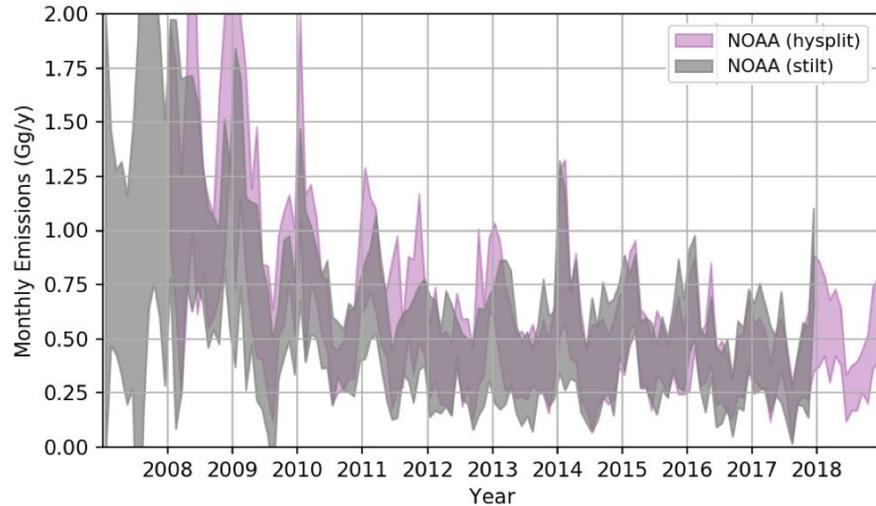
User Emissions = (Decrease in Storage Inventory) + (Acquisitions) – (Disbursements)

- **Subpart SS – Eq. SS-6**

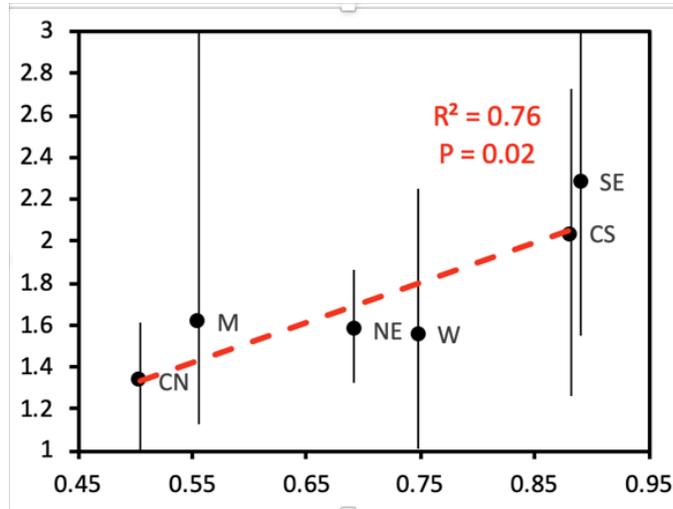
Emissions from Equipment Installation = (Total Mass used to Fill Equipment) + (Total Mass used to charge Equipment Prior to Leaving the Manufacturer Facility) – (Total Nameplate Capacity Installed at Electric T&D Facility)

- Emissions that occur during installation while filling the equipment off-site from the electrical equipment manufacturing facility must be calculated and reported by the electrical equipment manufacturer under Subpart SS until the title of the equipment has transferred to the electric power T&D entity.
- Once the title has transferred to the equipment user, the subpart DD facility is responsible for reporting emissions even if third-party conducts installation.

Seasonal SF₆ Trends



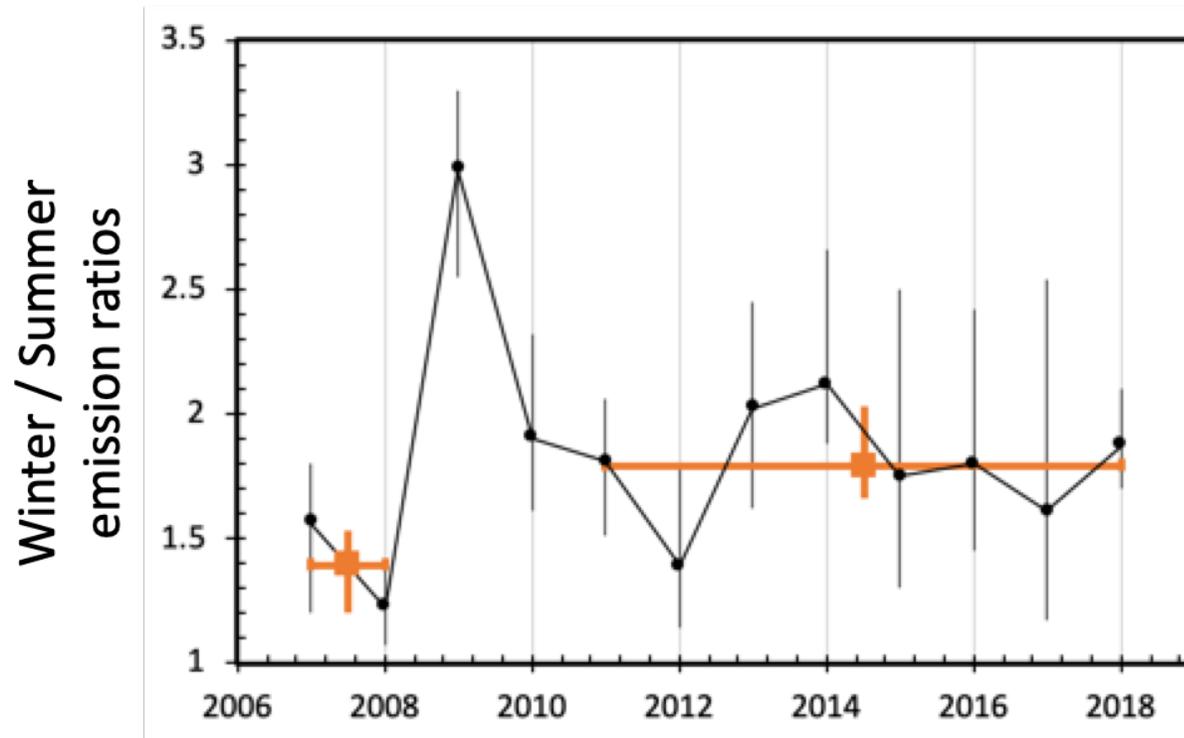
Winter / Summer emission ratios
derived by atmospheric observations



Fractions of regional ETD emissions in 2019 (EPA)

- Atmospheric measurements show persistent seasonal variations, with the highest emissions in the winter.
- SF₆ use and emissions not expected to vary seasonally for magnesium or electronics production.
- Based on discussions with ET&D sector, higher winter SF₆ may be due to increased servicing of electrical equipment during off-peak (cooler) months. In addition, leaks may be larger in the winter due to hardening of seals during cold weather.
- Seasonal variation is most pronounced in regions of the country where the majority of SF₆ emissions are from ET&D, as is the case in the South.

Seasonal variation apparently grew between 2006-8 and 2011-18.



Source: Source: Lei Hu et al., submitted, 2022.

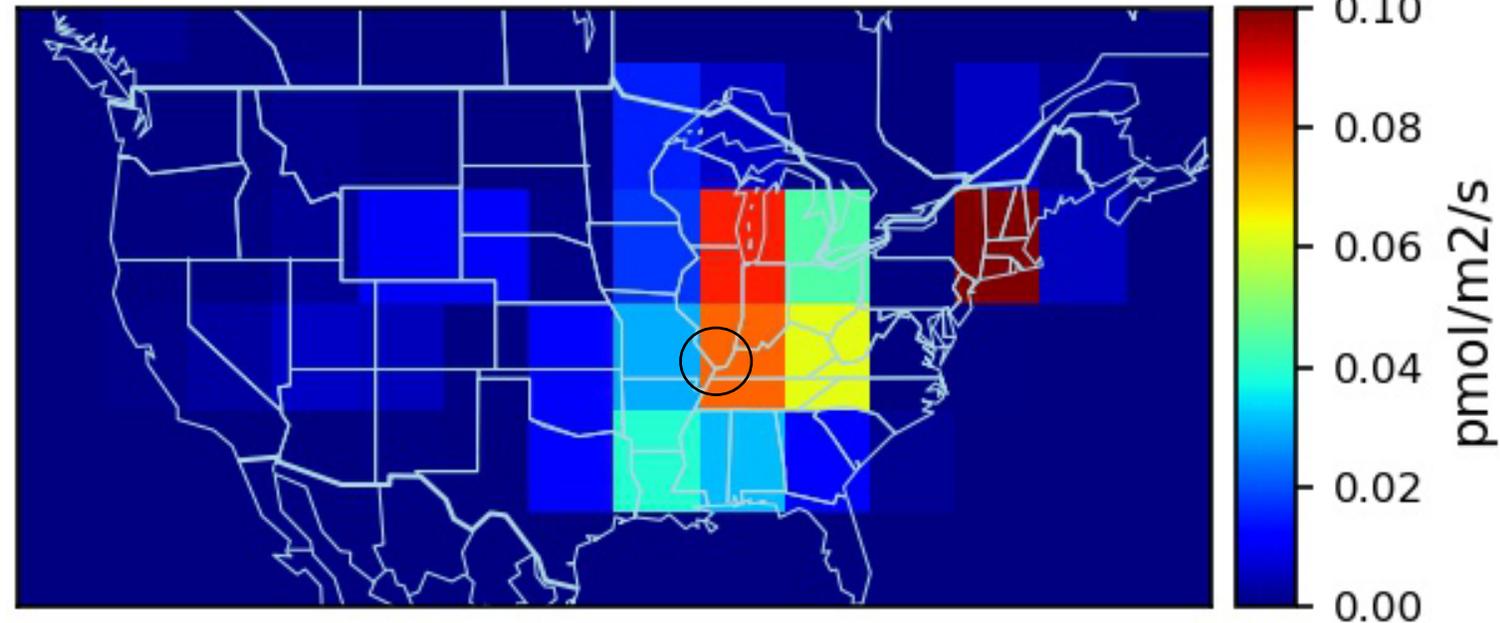
- Also see changes in seasonal variation over the time series.
- Largest variation seen in 2009, when Great Recession reduced semiconductor and magnesium production but didn't affect ET&D.
- Observe statistically significant difference between 2007-2008 variation and 2011-2018 variation.
- **Challenge:** This contradicts our hypothesis that underestimate from ET&D sector is primarily responsible for 2007-2010 overall underestimate.

Likely Source of Remaining Gap: SF₆ Production Facility

Estimated Decrease in Emissions Between 2008 & 2011-18 means
(from inversion)

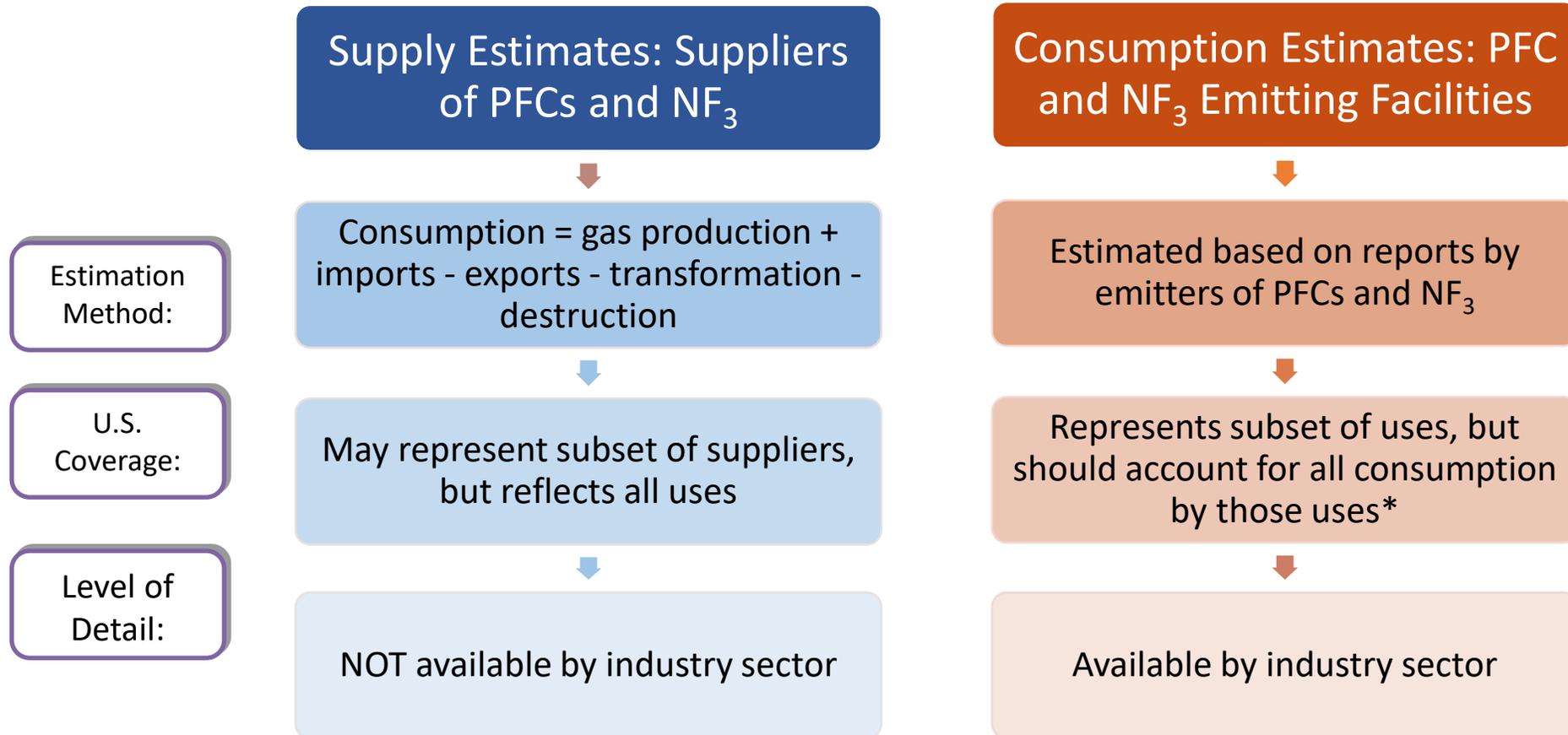
- Uses/sources other than ET&D include
(bold=current in US GHGI):

- **Source of fluorine for electronics manufacturing**
- **Cover gas for magnesium production and processing**
- Through 2010: Emissions from SF₆ production facility
- Military uses (e.g., AWACs, torpedo propellant)
- Insulator in research and medical accelerators
- Other medical applications
- Tracer gas and others



Once we account for (1) higher 2007-10 emissions from non-reporting ET&D facilities, and (2) 2007-10 emissions from the SF₆ production facility, mix of sources is consistent with seasonal variation seen in 2007 and 2008.

Overview of Supplies and Consumption Estimates



*after estimating emissions of non-reporters

US Consumption \neq Emissions

- Consumption $>$ emissions for some sectors
 - SF₆ is stored in electrical equipment (growing bank)
 - SF₆ is partially destroyed during electronics manufacturing
- Magnesium and electrical equip. manufacturing: SF₆ consumption = SF₆ emissions
 - Other consumption by electrical equipment manufacturing is counted as consumption by electrical equipment users (ET&D facilities)

Estimating SF₆ Consumption by Reporting Electric Power Systems and Electronics Manufacturers

- SF₆ acquired and disbursed by electric power systems is reported
- Electronics:
 - For facilities that do not abate emissions, back-calculate consumption based on reported emissions and default emission factors for each wafer size and process type.
 - For facilities that abate emissions, back-calculate hypothetical uncontrolled emissions based on reported abatement levels. Then calculate consumption of each gas based on relationship between emissions and consumption of that gas found for facilities that do not abate emissions.

Estimating Consumption by Non-Reporters

- **ET&D:** Estimate consumption of non-reporters based on their estimated emissions and growth rates and relationship found between reporter consumption and reporter emissions and growth rates.
- **Semiconductors:** Extrapolate SF₆ consumption estimated for electronics facilities reporting to the GHGRP to U.S. consumption based on index of electronics production (substrate area x number of layers).
- **Magnesium:** Use USGS estimates of production and EFs calculated from GHGRP and USGS data.
- **Elec. Equip. manufacturing:** Assume GHGRP accounts for 50% of consumption

Estimated SF₆ Consumption by Industry, 2010-2021 (metric tons)

